

Modelling of the Asian Tsunami off the Coast of Northern Sumatra

Niels Hvam Pedersen¹⁾, Peter S. Rasch¹⁾ and Tatsuaki Sato²⁾

1) DHI Water & Environment, Hoersholm, Denmark

2) Alpha Hydraulic Engineering Consultants Co, Ltd., Sapporo, JAPAN

E-mail : nhp@dhi.dk, ptr@dhi.dk, sato@ahec.jp

ABSTRACT

On December 26, 2004 a major earthquake occurred off the coast of Northern Sumatra measuring 9.0 on the Richter scale. The earthquake triggered a Tsunami that caused more than 250,000 casualties in the region. The historical tragedy revealed a need for urgent management for disaster prevention and/or relief, such as preparation of hazard maps, construction of a Tsunami warning system and education for local people in disaster response.

Immediately following the event, DHI Water & Environment (DHI) simulated the propagation of the Tsunami wave using the global setup of the flexible mesh version of MIKE 21, with a zoom in to the areas where the greatest effects were reported during December 26. In the first months of 2005 DHI, in cooperation with our Japanese partner company Alpha Hydraulic Engineering Consultants, have been gathering information relating to both the fault parameters of the quake and the initial shape of the water level displacement, furthermore, as many observations as have been possible.

This paper describes the use of the additional information and the advances that has been made in describing the Asian Tsunami wave.

Key Words : *Asian Tsunami, Model study, December 26, MIKE 21, and hazard map*

1. INTRODUCTION

A Tsunami wave can typically be generated as a result of sizeable earthquakes, which generates an instantaneous displacement of the sea-bottom, and thus a displacement of the sea surface. This displacement in turn generates a wave, which behaves as a shallow surface wave.

As Tsunamis travel across the open oceans, the amplitude of the wave of only a few centimetres is hardly noticeable. However, as they approach shore they will gradually build up and in areas where the topography of the seabed is especially suited they will reach heights of 10+ meters. The speed at which the Tsunamis travel of up to 800 km/h (500 mph) over the open ocean, slowing to 30-100 km/h as they reach shore, combined with the extreme shoaling is what makes them so disastrous.

MIKE 21 rectilinear has previously been used to simulate the Atlantic Tsunami of 1755 (ref. Webpage) in the waters west of Portugal. This Tsunami caused devastation to the nearby cities, especially Lisbon and Casablanca on the Moroccan coast. The experiences from that study, which was carried out as part of a feasibility and design study of a power plant on the Moroccan coast, facilitated the quick and optimum set-up of MIKE 21.

Recently MIKE 21 has also been used to study the effect of the major 1960 Chilean earthquake on the Chacao Channel entrance, Chile. The 1960 earthquake created a tsunami that destroyed not only the Chilean coast, but also damaged coastal installations in Hawaii and Japan. The tsunami formed up into a 15 m high bore on the Pacific Ocean beaches north and south of the Chacao Channel entrance.

Following the immediate response to the Asian Tsunami disaster, DHI has analysed the Asian Tsunami using the state of the art modelling package MIKE 21. The rectilinear MIKE 21 version, as well as the flexible mesh (FM) version with parallel computing method, has been applied to calculate the propagation of the wave.

The simulations have been setup with a finer geomorphological resolution in selected areas of interest, i.e. Banda Aceh region in Indonesia and Phuket Island in Thailand. The detailed resolution near land and large gradients in water depth are necessary to describe the local shoaling effect of the Tsunami, and especially MIKE 21 FM model makes this bathymetry modelling quite easy.

Initial surface elevation maps for the Tsunami based on the USGS fault model, DCRC fault model and some original fault models have been used in the simulations. Original initial maps were generated from some series of fault parameters that have a magnitude of 9.1 on the Richter scale using the Alpha geological model with the international standard theory (Manshinha and Smylie, 1971). Calibrations of these models are implemented with some measurements, such as those presented by NOAA. The effect of the land displacement has also been included in the MIKE 21 simulations using the land slide option.

2. HYDRODYNAMIC SET-UP OF A GLOBAL MODEL IN A FLEXIBLE MESH

We have attempted to simulate the Tsunami propagation using an operational global 2D model with flexible mesh (MIKE 21 FM). With this flexible mesh we are able to zoom into interest areas where the Tsunami have had the most devastating impacts, in addition to the Tsunami global propagation. The model includes 429,459 mesh elements and the time step interval setting is 2 seconds

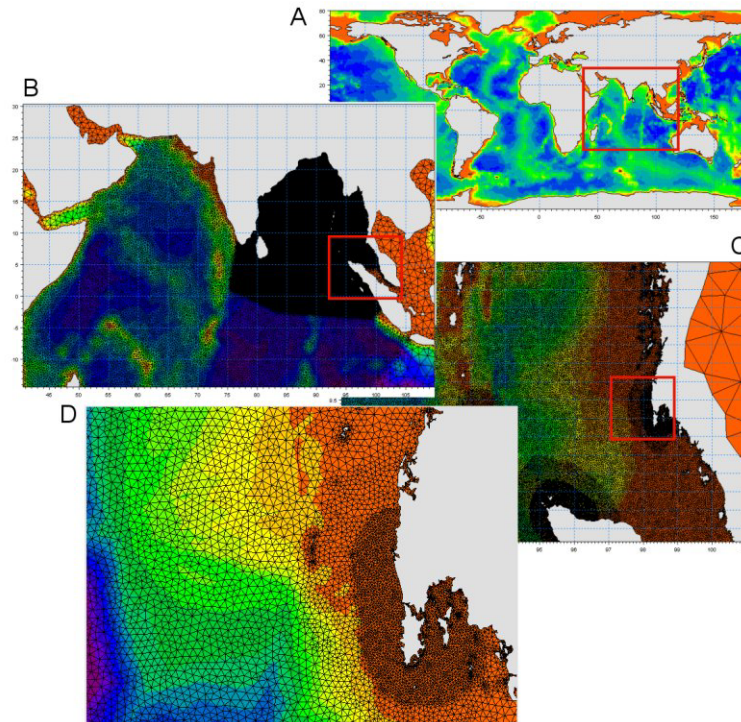


Figure 2.1 The mesh used for the MIKE 21 FM simulation, with a zoom to various regions.

2.1 Initial Conditions

To create initial conditions we used the geological model (the ALPHA geological model) to generate initial maps from a series of fault parameters as shown in Table 2.1.

Table 2.1 Fault parameters for initial surface elevation.

Fault parameters	Fault1
Origin X (deg.)	1.500
Origin Y (deg.)	94.000
Strike angle (deg)	335
Fault length (km)	900
Fault width (km)	150
Depth of the upper fault (km)	10
Dip angle (deg.)	8
Slip angle (deg.)	110
Dislocation (m)	11
Total moment magnitude (Mw)	9.1

The model is based on Mansinha and Smylie's theory (Mansinha and Smylie, 1971). It calculates a displacement of the seabed that results from seismic fault movements in the earth's crust, assuming that the crust consists of an elastic body and fault shape is rectangular. In this model, the displacement depends on Poisson's ratio.

The initial condition for MIKE 21 FM is shown in Fig. 2.2. This gives a best and quick guess for the initial surface elevation, which is the most simple fault model with 9.0 Mw.

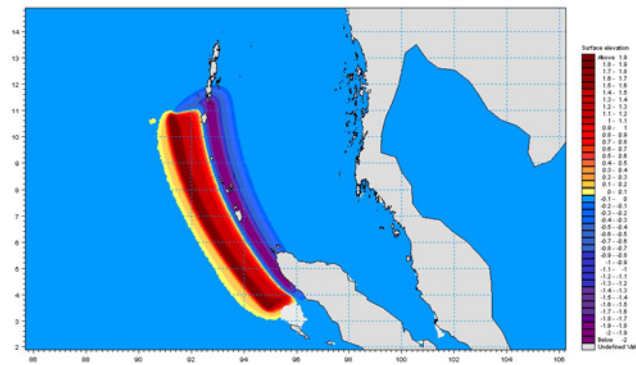


Figure 2.2 The initial surface elevation for FM modelling.

2.2 MIKE 21 FM Global Results

Using the initial field from above, the model generates a Tsunami, which propagates across the Indian Ocean. A few snapshots are shown below.

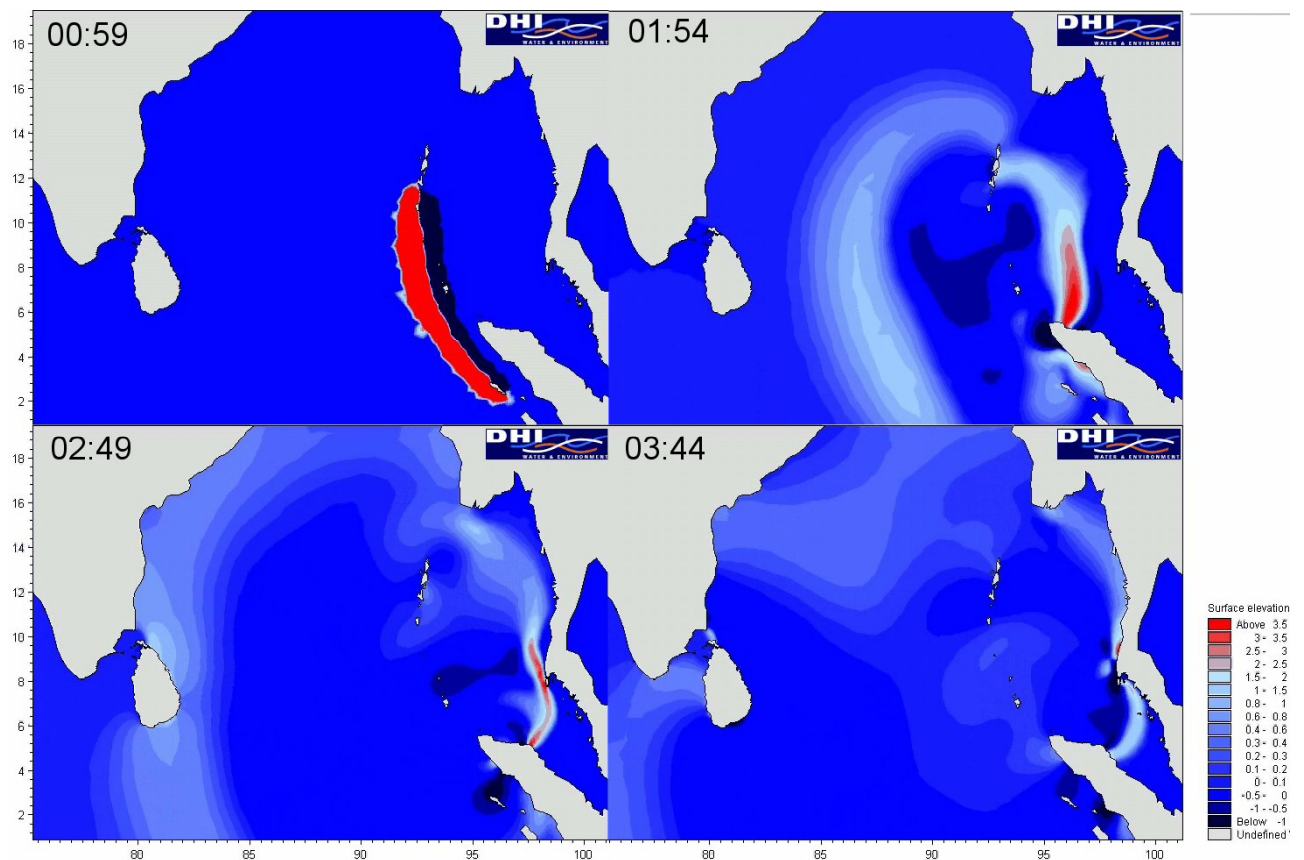


Figure 2.3 Wave propagation across the Indian Ocean.

This initial model is too coarse to simulate the Tsunami because the explicit scheme requires high resolution to avoid damping. Further refinements are ongoing at DHI, but we will in the remainder of this paper concentrate on the rectilinear version of MIKE 21.

3. HYDRODYNAMIC SET-UP REGIONAL MODEL

We have attempted to find out an optimum initial condition for the Tsunami to explain observed tsunami propagation situation well with MIKE 21 (rectangular grid version).

The model is nested simulation with 9720m and 3240m as grid scale. The time step interval is 60 sec.

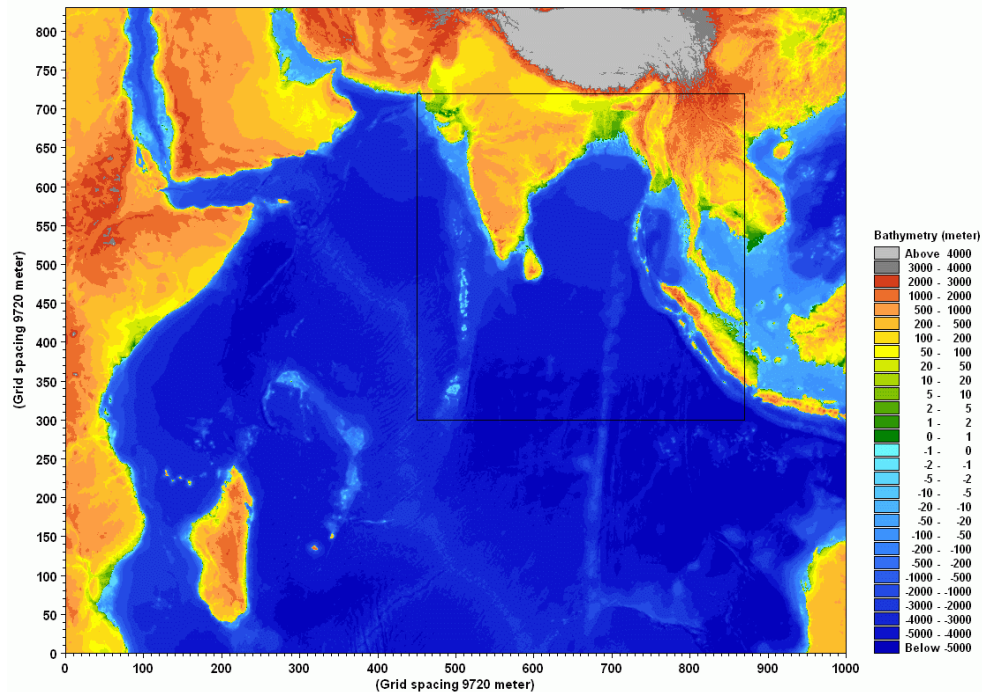


Figure 3.1 Regional bathymetry.

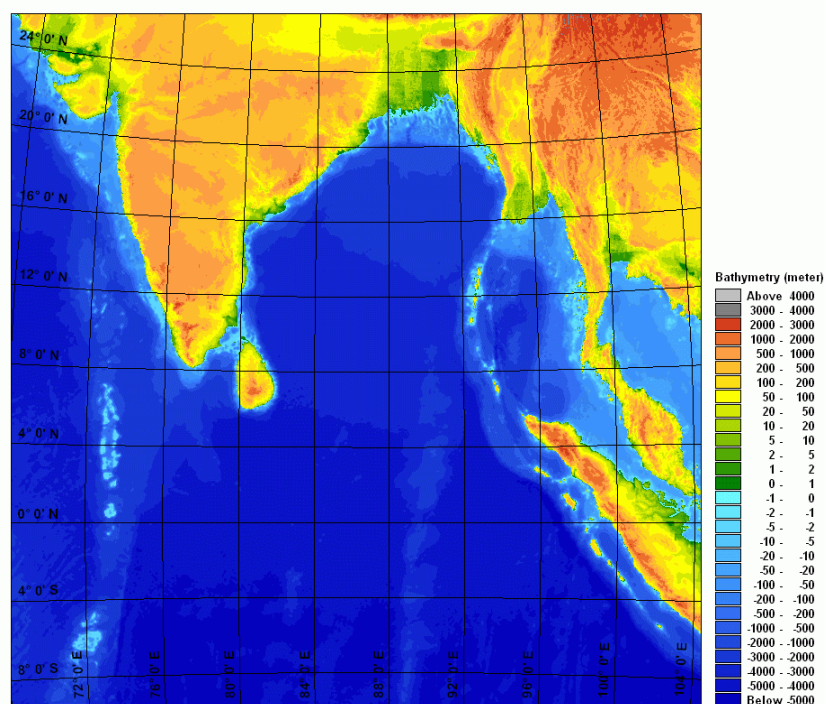


Figure 3.2 Local bathymetry.

3.1 Initial Conditions

We have attempted to find an optimum initial condition for the Tsunami to explain the observed Tsunami propagation situation well.

First of all, we tried two initial maps presented from other institutes as preliminary simulation. One is from the U.S. geological survey (USGS model, 9.0Mw, Fig.3.3 Left) that results from the analysis of seismic waveforms. The other is from the Disaster Control Research Center in Japan (DCRC model3, 9.1Mw, Fig. 3.3 Right) that results from some trials of Tsunami simulation.

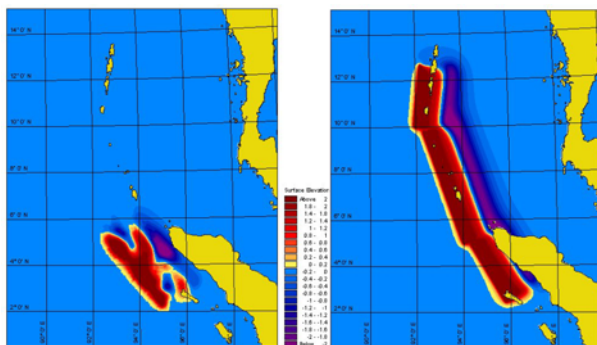


Figure 3.3 Initial surface elevation (Left: USGS model, Right: DCRC model3)

The fault parameters for the DCRC-3 fault model are shown below.

Table 3.1 Fault parameters for initial surface elevation (DCRC model3).

Fault parameters	Fault1	Fault2	Fault3
Origin X (deg.)	2.500	5.000	10.000
Origin Y (deg.)	95.750	94.000	92.000
Strike angle (deg)	329	340	5
Fault length (km)	330	570	300
Fault width (km)	150	150	150
Depth of the upper fault (km)	7	7	7
Dip angle (deg.)	15	15	15
Slip angle (deg.)	110	110	110
Dislocation (m)	11	11	11
Total moment magnitude (Mw)	9.1		

*) USGS model was calculated with inhomogeneous fault model.

As next step, we tried two new initial maps based on the analysis of preliminary results in cooperation with Alpha Hydraulic Engineering Consultants Co.Ltd (ALPHA model 1 and 2, 9.1Mw each, Fig. 3.4, table 3.2 and 3.3). Finally, we tried the modified initial map based on the analysis of former simulation (ALPHA model 3, 9.1Mw, Fig. 3.4, fault parameters table 3.4).

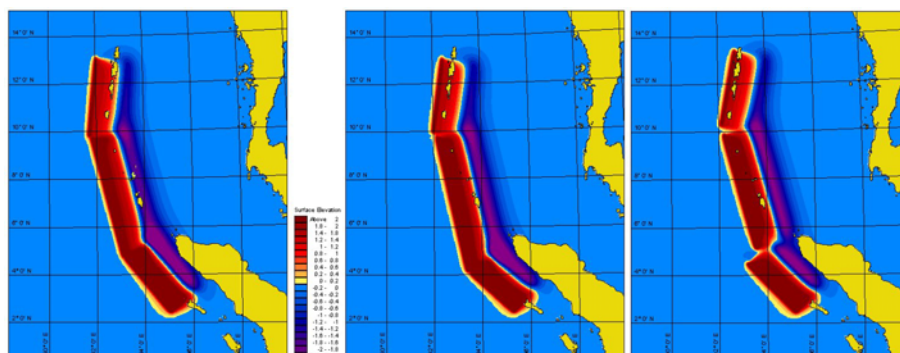


Figure 3.4 Initial surface elevation (Left:ALPHA model1, Middle:ALPHA model2, Right:ALPHA model3)

Table 3.2 *Fault parameters for initial surface elevation (ALPHA model1).*

Fault parameters	Fault1	Fault2	Fault3
Origin X (deg.)	2.500	4.800	9.800
Origin Y (deg.)	95.000	93.070	91.730
Strike angle (deg)	320	345	5
Fault lenght (km)	330	570	370
Fault width (km)	150	150	150
Depth of the upper fault (km)	7	7	7
Dip angle (deg.)	15	15	15
Slip angle (deg.)	110	110	110
Dislocation (m)	15	10	7
Total moment magnitude (Mw)	9.1		

Table 3.3 *Fault parameters for initial surface elevation (ALPHA model 2).*

Fault parameters	Fault1	Fault2	Fault3
Origin X (deg.)	2.500	4.200	9.960
Origin Y (deg.)	92.250	93.360	92.030
Strike angle (deg)	312	347	7
Fault lenght (km)	270	640	350
Fault width (km)	150	150	150
Depth of the upper fault (km)	7	7	7
Dip angle (deg.)	15	15	15
Slip angle (deg.)	110	110	110
Dislocation (m)	13.5	11.5	7
Total moment magnitude (Mw)	9.1		

Table 3.4 *Fault parameters for initial surface elevation (ALPHA model 3).*

Fault parameters	Fault1	Fault2	Fault3
Origin X (deg.)	2.500	5.150	10.250
Origin Y (deg.)	95.100	93.500	92.150
Strike angle (deg)	315	344	10
Fault lenght (km)	320	550	360
Fault width (km)	150	150	150
Depth of the upper fault (km)	7	7	7
Dip angle (deg.)	15	15	15
Slip angle (deg.)	110	110	110
Dislocation (m)	13.5	12	7
Total moment magnitude (Mw)	9.1		

3.2 Regional Results

We validated each result with the satellite Tsunami propagation images (2 hrs, 3:15 hrs and 8:50 hrs after the earthquake) from the National Oceanic and Atmospheric Administration in U.S.(NOAA).

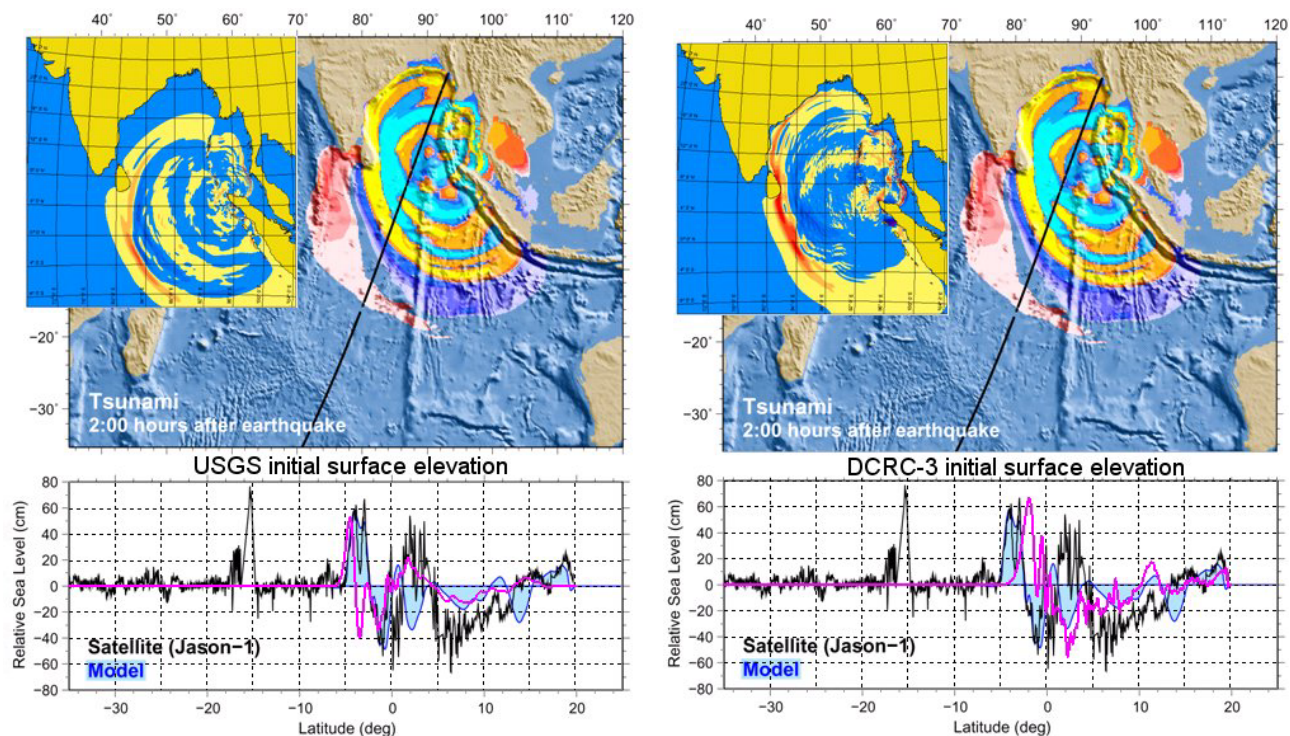


Figure 3.5, Comparison between NOAA SSH, NOAA model and MIKE 21 rectilinear with initial surface elevations from USGS (Left) and DCRC-3 (Right).

Preliminary results (the results for USGS model and DCRC model 3 show that the south part below 5 deg. N Lat. of USGS result is better than that of DCRC model 3, while the north part above 5 deg. N Lat. of DCRC model 3 seems to be better than that of USGS model. Therefore, we suppose that the next trials should be similar to USGS model for south part of the map, and inversely similar to DCRC model 3 for north part of the map.

For the USGS model the sea level change along the satellite trace is similar to the measurement around the equator at 2 hours after the earthquake. However, wave amplitude is quite lower than the measurement especially for northern part. That is because this initial elevation area concentrates at off the west coast of Northern Sumatra, and this also results in the lower wave height around the Phuket area.

For the DCRC model 3 the result at 2 hours after the earthquake has a little similar trend to the measurement above 5 deg. N latitude. However, the wave phase is quite different between simulation and measurement below 5 deg. N latitude. This difference suggests that a southern part of initial elevation should be located further off from the coast of Northern Sumatra.

The series of tests with the Alpha geological model (Alpha model 1 – model 2 – model 3) are calibrated to the SSH NOAA observations and model, and show considerable improvements.

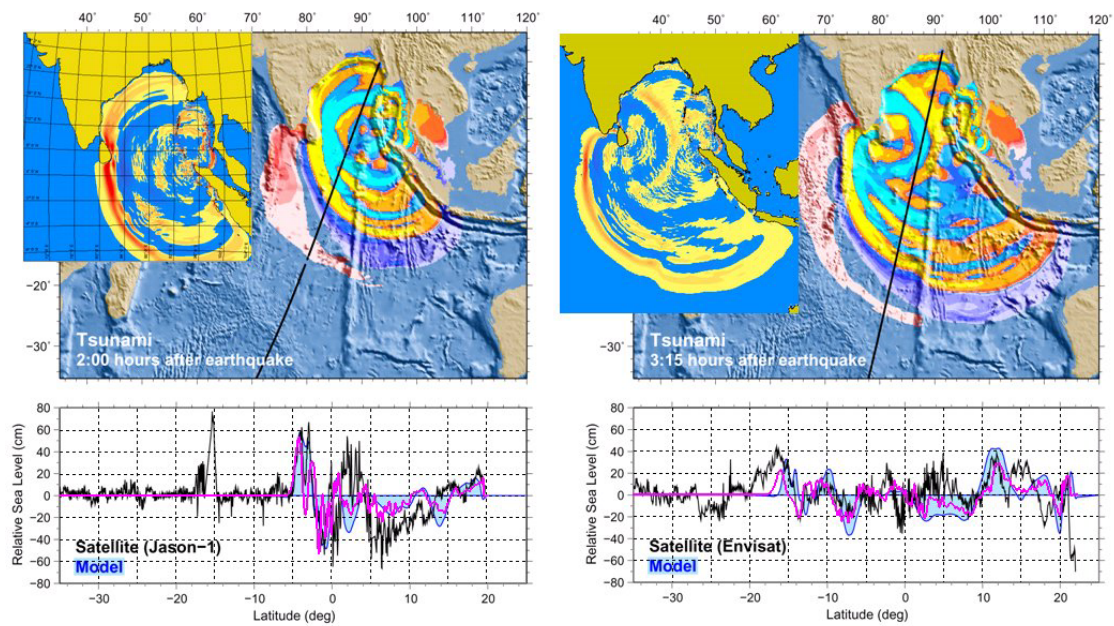


Figure 3.6, Comparison between NOAA SSH, NOAA model and MIKE 21 rectilinear with initial map from Alpha model 3.

For direct comparison to the satellite SSH images, we have extracted the satellite track from the MIKE 21 output, and compared them to the NOAA tracks.

In the ALPHA model 1, the result describes general phase characteristics of the sea level change along the satellite trace well. However, wave amplitude is bigger than the measurement between 5 deg.S and the equator. This suggests that a southern part of initial elevation should have lower wave height.

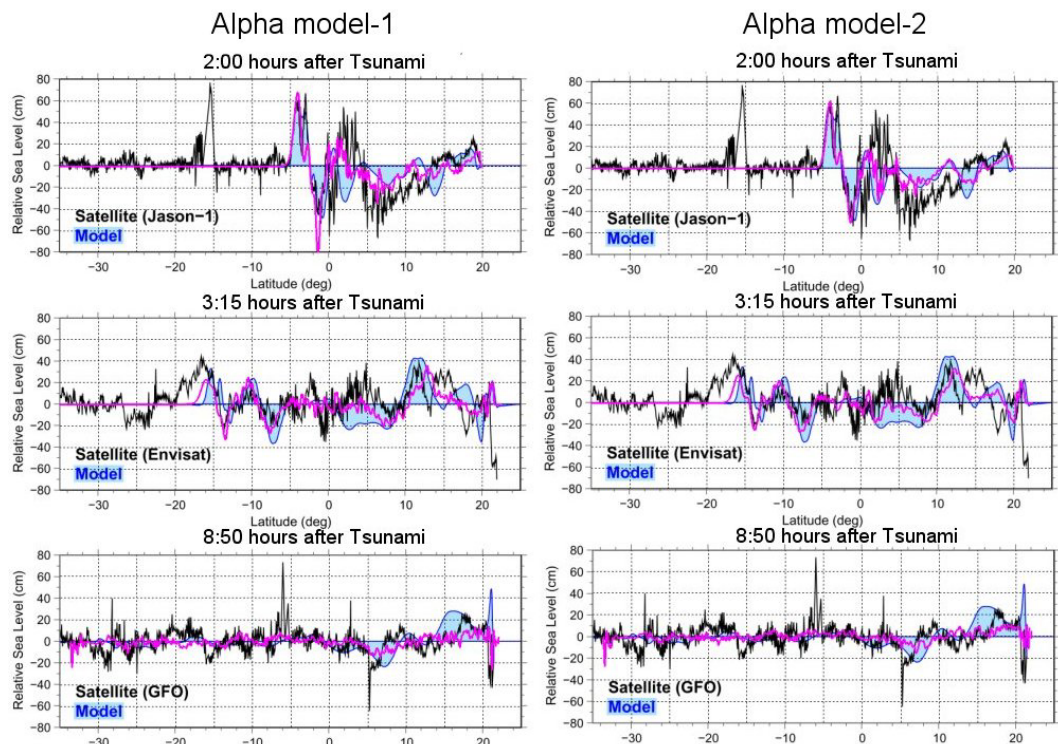


Figure 3.7, Alpha model-1(left) and model-2(right) compared to NOAA SST tracks.

With the initial field from ALPHA model 2, the result at 2 hours after the earthquake describes phase characteristics of the sea level change along the satellite trace well. However, wave amplitude is bigger than the measurement between 5 deg.S and the equator. This suggests that a southern part of initial elevation should have lower wave height.

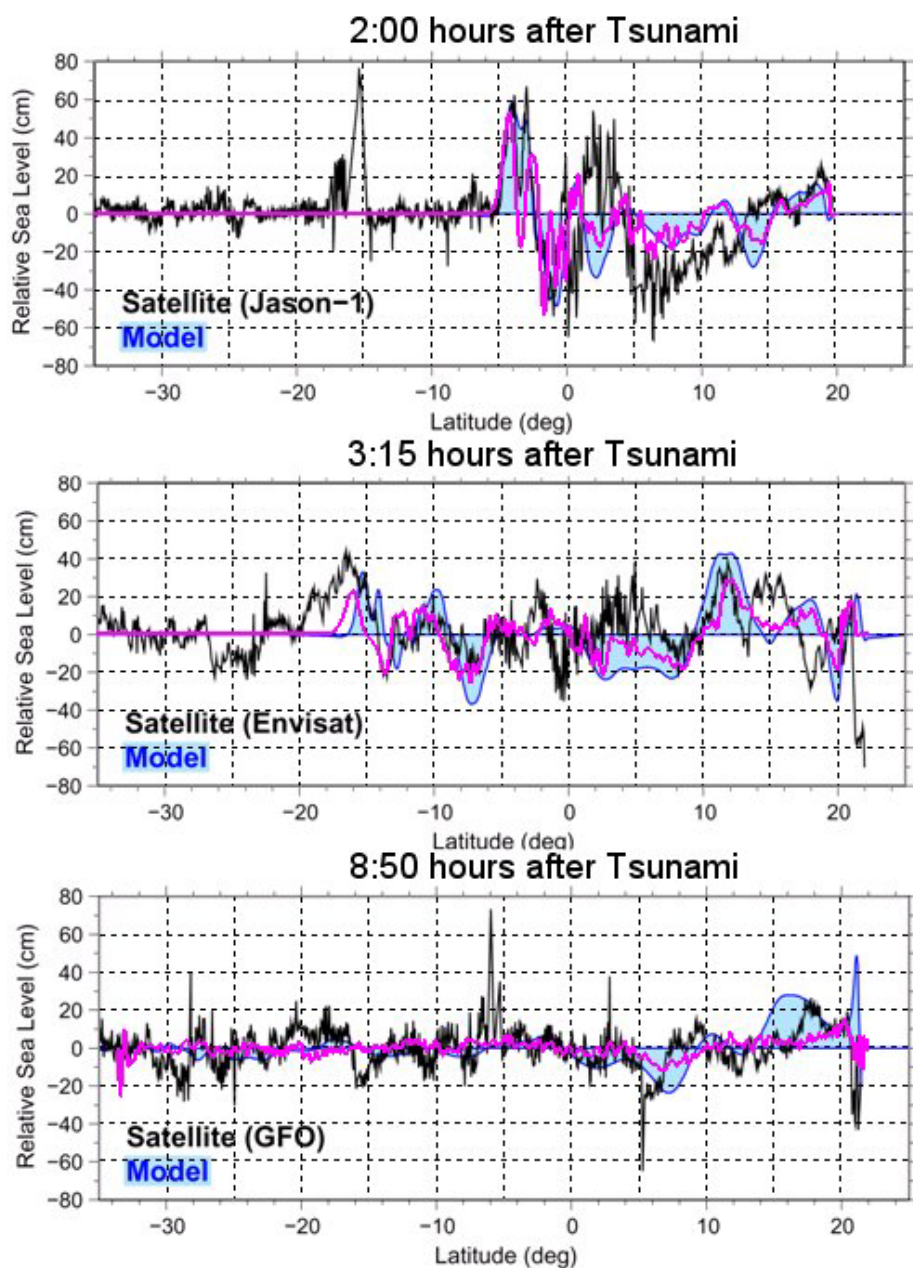


Figure 3.8, Alpha model-3 compared to NOAA SST tracks.

Finally with ALPHA model 3 initial waterlevel, the result is almost similar to ALPHA model 2, but this includes a little improvement of wave reproduction beneath the equator.

3.3 Local Results

As described in the introduction the evaluation of the models in near shore areas requires both high resolution and accurate bathymetry data. We did however investigate some of the eyewitness accounts relayed on internet and in the media. One of these was described in EOS (see References), and we checked Tsunami arrival time in Sri Lanka for this result (Fig. 3.9).

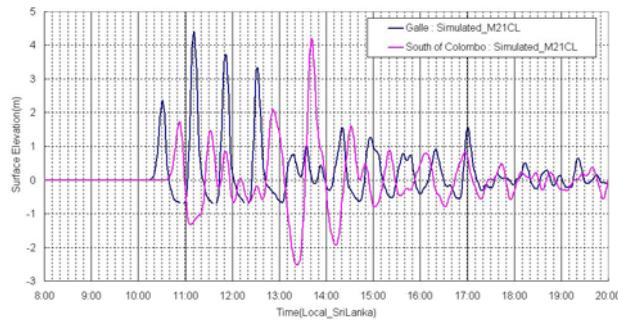


Figure 3.9 Calculated wave fluctuations around south Sri Lanka (ALPHA model3).

(Red arrows show the Tsunami peak timing from witness in Ahungalle, 30 km north of Galle)

According to the witness (EOS), the Tsunami peaks were at approximately 0930, 1010(the big one), 1110, 1150, 1235, 1255, etc., local time at Ahungalla, Sri Lanka (about 30 km north of Galle), and 3rd and fourth surges were larger than the first. The simulated results show good agreement with this witness.

In videos recorded by various witnesses to the event one can on locations east of the fault line see the first arrival of the negative wave, and also see the extreme shoaling causing a continuous wave in exceedence of 10 meters in height, also eyewitnesses reports several waves on top of a larger wave. All these effects will not be captured by the hydrodynamic models, because of the extremely high resolution required.

To illustrate how the height of a tsunami wave changes when it approaches the shore and inundates an urban area, a number of Boussinesq type model simulations have been made with DHI's MIKE 21 BW model. This model includes the processes that determine how the tsunami (and the local inundation) behaves in coastal areas, for example processes like non-linear shoaling, diffraction, reflection, wave breaking and run-up.

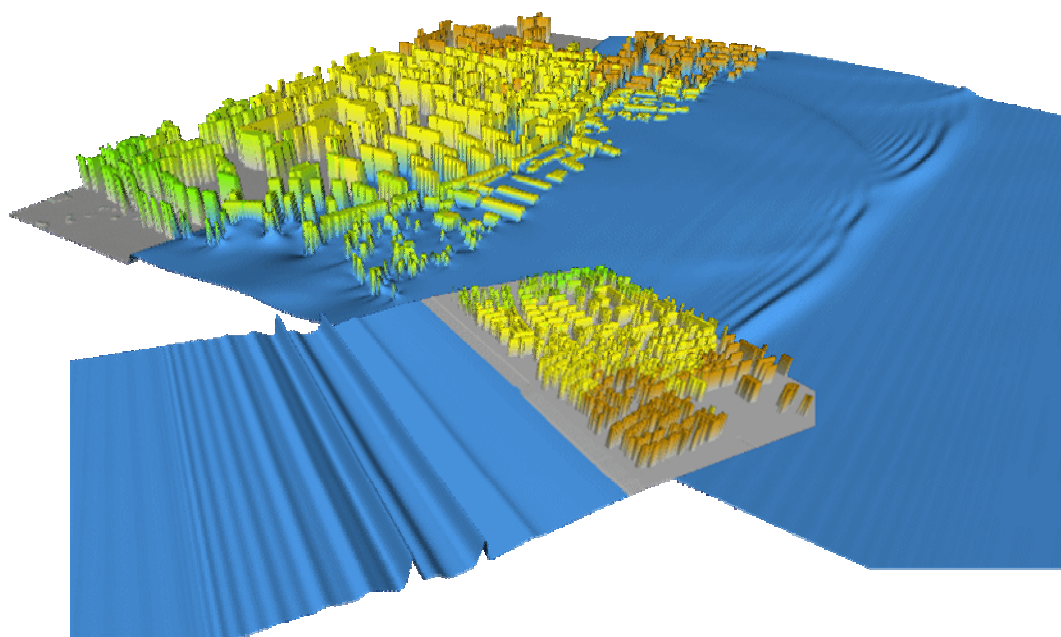


Figure 3.10 Wave propagation, transformation and inundation simulated by using DHI's Boussinesq Wave Model, MIKE 21 BW. The figures show the effect of shoaling, wave breaking and reflection from land and buildings.

4. DISCUSSION

Two different MIKE 21 model set-ups with different grids have been used to describe the spreading of the Asian Tsunami throughout the Indian Ocean. The propagation depends primarily on the method used to determine the initial conditions for the wave, and secondly on the bathymetry of the area. From the relatively few measurements available all indications show that both grids correctly describe the timing of the wave both in the deep waters and on the shallow shelf.

The rectilinear MIKE 21 matches the amplitude of the wave in the deep ocean as compared to satellite determined SSH. The flexible mesh model has not been run with sufficient horizontal resolution to compensate for the damping that occurs with the fast travelling wave in combination with the explicit solution and the Courant criteria of $\frac{1}{2}$, and therefore the amplitude dissipate too quickly on the deep ocean.

As the wave approaches shore and the detailed local bathymetry determines the degree of diffraction and shoaling, which in turn determines how far inshore the wave will travel, the resolution of the models becomes the determining factor. Near Galle on the Sri Lankan west coast where the wave has been diffracted around the southern tip and the main part of the shoaling occurs on the west side, it appears in figure 3.9 that the model resolution is sufficient to describe these processes.

For the local effects on the leeward side of Phuket in Thailand near Krabi and south thereof, the area consists of many islands and with a bathymetry full of details, and the resulting wave is a combination of the diffracting wave around Phuket with the wave that travelled down and up through the Malacca strait. In this case, resolution is most likely too coarse - although the fine resolution in the flexible mesh model seems to capture some details, and also the rectilinear model gets the overall picture. Unfortunately, at the time of writing we do not have sufficiently good measurements available to confirm the local effects in the South of Thailand.

It has been shown that despite very limited data, the nature of the Tsunami is such that the overall propagation can be accurately described with the numerical engines used, as long as they have

sufficient resolution in space. This becomes more acute as the wave approaches shore, where the local bathymetry needs to be both accurately described and resolved in the models.

It has been suggested to use models in a future warning system in this region – and the modelling described above confirms the feasibility of this approach. The nature of the initial elevation however needs, to be determined so accurately that you can not do the modelling in a fast response situation to anything other than the timing of impact on various shores. Instead modelling should be used to create an atlas of the coast describing potential high impact areas – Hazard Maps. This can be done by using storm surges and other events to calibrate the bathymetry of high resolution local models.

REFERENCES

Manshinha, L. and Smylie, D.E. (1971): The displacement fields of inclined faults, *Bulletin of the Seismological Society of America*, vol.61(5), pp. 1433-1440.

DHI <http://www.dhisoftware.com/general/News/Tsunami/index.htm>

USGS http://neic.usgs.gov/neis/bulletin/neic_slav_ff.html

DCRC <http://www.tsunami.civil.tohoku.ac.jp/hokusai2/topics/04sumatra/index.html>

NOAA <http://www.noaaneews.noaa.gov/stories2005/s2365.htm>

EOS American Geophysical Union, transactions volume86(2) 11 January 2005

ALPHA HECC <http://www.ahec.jp/>